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A Generative Approach for Design Evaluation and Partner Selection for Agile Manufacturing

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A Generative Approach for Design Evaluation and Partner Selection for Agile Manufacturing

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Abstract

An agile manufacturing firm forms partnerships with other manufacturers as necessary to design and manufacture a product quickly in response to a market opportunity. In order to form a successful partnership, the firm needs to create a superior design and select the partners that best fit the partnership's scope. In this paper we consider the intrinsic relationship between design evaluation and partner selection. The paper presents a generative approach that a design team can use to obtain feedback about a new product embodiment based on high-level process plans and on the manufacturing capabilities and performance of potential partners. Using this information, the design team can improve their design and identify the potential partners that best fit its manufacturing requirements. The primary application of this work is to certain types of mechanical and electronic products.

1 Introduction

Ideally the partnership of agile manufacturing firms is a virtual enterprise in which each manufacturer realizes a portion of the product design and cooperates with the other members of the enterprise to lower the product's cost, improve its quality, and reduce the timespan necessary to bring the product to market. In the virtual enterprise, the partners exchange electronically information concerning design, process planning, production planning, inventory management, testing, distribution, and billing. In addition, the partners should establish business processes that allow them to exchange such data and to process the necessary transactions.

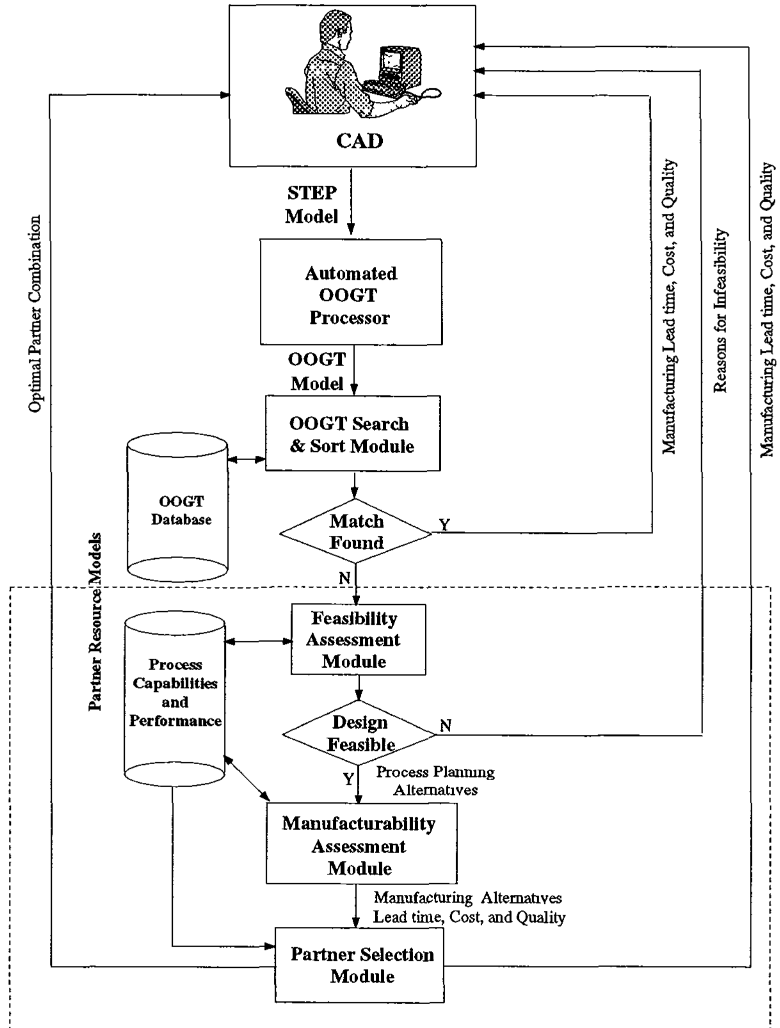

Figure 1: Design evaluation and partner selection approach

This paper addresses a special case of the virtual enterprise: one firm designs the product and joins with other firms for the product's manufacture. In order to form a successful partnership, the firm needs to create a superior design and select the partners that best fit the scope of the virtual enterprise. This study supports both needs. First it provides methods to evaluate a proposed design with respect to the capabilities of candidate partners. Second, it provides tools for selecting those partners that best fit the design's requirements. Note that we consider those decisions to be intrinsically coupled, and thus we treat them simultaneously. The integration of design evaluation and partner selection allows critiquing of the design considering the partner-specific strengths that are related to the product's manufacturing requirements (not the manufacturing plant's general performance). It also provides vital design feedback at a point when modifications to improve the fit between the design and the partners are less costly.

Our methods are of two types, variant and generative, and form an overall approach overviewed in Figure 1. This paper focuses on the generative methods; the variant ones have already been reported in [8]. To provide appropriate background, in the following paragraphs we overview the entire approach. According to Figure 1, the output of the designer's CAD system is translated and stored in an integrated product model. This model uses the data definitions of STEP, the international Standard for the Exchange of Product Data (ISO 10303 [33]), and thus supports the free exchange of data between the firm and its partners.

Both the variant and generative design evaluation methods require more abstract product information than that in the STEP-based product model: Group Technology (GT) codes are used in searching for and retrieving similar products; more detailed data about the product attributes captured by the GT code are used for high-level process planning in the generative portion of the approach. This information is captured in the Object-Oriented Group Technology (OOGT) model. To derive the OOGT information from the STEP product representation, we have developed a set of algorithms and implemented them in the Automated OOGT Processor of Figure 1. (See Section 7.)

In the variant portion of the approach (OOGT Search and Sort), the designer exploits the concise nature of GT codes to search quickly for similar products in the product databases of candidate partners. The designer uses the information in the OOGT models of the identified products to sort the products based on more accurate similarity measures. The information about the designs, process plans, and performance of the similar products (if any) is valuable in evaluating the new product design in terms of important metrics such as cost, expected quality, and lead time. The manufacturers of the similar products are also candidate partners for the virtual enterprise. Finally, the design of cost-effective, high-quality similar products may suggest useful changes to the current product design.

If no adequate information is obtained from the variant design evaluation, the designer uses the generative method, which comprises two steps. The first step (Feasibility Assessment) generates feasible manufacturing alternatives. The system uses generic data about manufacturing processes and specific information about the process capabilities of the candidate partners to construct feasible process plans or identify features of the design that are infeasible. The feasible process plans specify the sequence of manufacturing operations, the candidate partners who could perform these operations, and the design attributes to be realized at each operation. (The process plans do not describe the tooling, fixtures, or other specific manufacturing instructions necessary for actual production.) In case of infeasibility (within the universe of candidate partners), this step identifies for the designer the related attributes to be revised. The second step (Manufacturability Assessment) also uses both generic data about manufacturing processes and specific performance measures about the processes of the candidate partners to evaluate each feasible process and partner combination with respect to cost, quality, and lead time. In addition, in this step the designer can determine those attributes that have major contributions to the design cost, quality, and lead time. This information may be used for redesigns that improve the design's performance within the universe of partners. Once the design evaluation is complete, the designer may sort the alternative high-level process plans on selected criteria, identify the partners that

form the most desirable plan, and receive feedback on the plan's expected cost, quality, and lead time.

Our approach has been applied to flat mechanical products and microwave modules (MWMs), which comprise flat mechanical substrates of complex shape, an artwork layer, and electrical components.

The remainder of this paper is structured as follows: Section 2 reviews some related work on agile manufacturing, vendor selection, and design critiquing. Section 3 reviews product and manufacturing resource models. Section 4 discusses the generative high-level process planning procedure. Section 5 discusses the design evaluation procedure. Section 6 reviews the partner selection method. Section 7 describes the software system that implements our approach. Section 8 presents the conclusions of our work.

2 Background

Agile Manufacturing

Agile Manufacturing is an all encompassing, enterprise-wide strategy that targets the ability to remain competitive in an environment of continuous change. The concept of agility was first discussed by Dove and Nagel [48, 55]. This original work has sparked significant research and development efforts in both industry and academia on diverse aspects of agility. For example DARPA is currently sponsoring over twenty projects under its Agile Manufacturing program in areas ranging from collaborative design of electromechanical products to virtual enterprises. Furthermore, the National Science Foundation and DARPA are sponsoring Agile Manufacturing Research Centers focusing in the electronics [25], aerospace [38], and machine tool industries [14].

Current agility-related work on virtual enterprises (or distributed manufacturing) includes the AIMS (Agile Infrastructure for Manufacturing Systems) program, which is developing business processes and information technology for using the Internet [54]. Business processes under study include standardized trade agreements, sourcing pre-qualification, pre-defined protocols, and standard component libraries. Information technology under development includes interfaces, protocols for manufacturing services, brokers and shop floor applications. The NIIIP (National Industrial Information Infrastructure Protocol) [49] is developing and demonstrating common communication protocols, an object technology base for system and application interoperability, specification and exchange of standard information models, and cooperative management of processes within virtual enterprises.

The Electronics Agile Manufacturing Research Institute at the Rennselear Polytechnic Institute is developing an information infrastructure that enables collaboration between customers, suppliers, and key departments such as marketing, design, and manufacturing [25]. The Agile Aerospace Manufacturing Research Center at the University of Texas at Arlington

is developing management guidelines for forming and operating virtual enterprises [66] and is studying current industrial efforts in this area. To date, they are focusing on four variables that influence agility [1]: communication interactivity, physical and cultural distance, technological compatibility, and motivation. The MIT/Lehigh Fast/Flexible Manufacturing project [72] is conducting field studies with the automotive and aircraft industries to identify the limitations of existing design and manufacturing activities that involve interactions between the customer and the partners and interactions between engineering and business processes.

By forming consortia of manufacturers and research institutions, the above-mentioned research efforts are attempting to address wide-ranging and complex problems of forming virtual enterprises. Much effort has focused on important business processes that must be in place to enable virtual enterprises as well as on the related information technology. The work described in this paper studies the opportunities that this new paradigm offers a design team to improve the product design in order to take advantage of partner capabilities.

Vendor Selection, Criteria, and Models

The vendor selection process has undergone significant change due to the increased expectations of customers in terms of quality, timeliness, and cost effectiveness, and due to the explosion in information systems engineering. Weber *et al.* [71] review and classify various articles related to vendor selection, and discuss the impact of Just-In-Time (JIT) manufacturing strategies on vendor selection. Monczka *et al.* [46] present the results of research with purchasing organizations about the perceived importance of supplier information. Gregory [21] presents a worksheet-based approach to evaluate supplier data in five areas: proposal responsiveness, technical expertise, quality, cost, and other. Diekmann [15] presents the results of a study on cost-plus contractor selection using an additive utility model, in which multiple objectives are formulated as scaled, linear combinations of single-attribute utility functions. This work evaluates the importance of cost exposure, company stability, quality of product and management capability in contractor selection. Roberts [57] presents a model to rate vendor delivery, which accounts for both quantity and time-related discrepancies. Russell and others [59, 60, 61, 62, 63] discuss contractor prequalification in the field of Civil Engineering construction and out-sourcing. These references present the knowledge acquisition method employed in the development of contractor prequalification models and the resulting system.

Information about manufacturing companies is necessary for the agile manufacturing functions of prequalification of partners, evaluation of product designs with respect to the individual capabilities of potential partners, and selection of the optimal set of partners. To our knowledge, no work to date has concentrated on the representation of company specific manufacturing capabilities and performance.

Manufacturability Evaluation

Evaluating the manufacturability of a proposed design involves determining whether or not it is manufacturable with a given set of manufacturing operations—and if so, finding the associated manufacturing efficiency.

In an attempt to increase the awareness of manufacturing considerations among designers, leading professional societies have published a number of manufacturability guidelines for a variety of manufacturing processes [2, 3, 5, 53, 70]. Some companies produced and used their own guidebooks for designers—one of the pioneers was General Electric [20].

Researchers have developed several different approaches to evaluate manufacturability of a given design [2, 19, 27, 37, 67, 17]. Existing approaches can be classified roughly as follows:

Direct or rule-based approaches [35, 36, 58] evaluate manufacturability from direct inspection of the design description: design characteristics which improve or degrade the manufacturability are represented as rules, which are applied to a given design in order to estimate its manufacturability. Most existing approaches are of this type. Direct approaches do not involve planning, estimation, or simulation of the manufacturing processes involved in the realization of the design.

Indirect or plan-based approaches [28, 29, 31] do a much more detailed analysis: they proceed by generating a manufacturing plan and examine the plan according to criteria such as cost and cycle time. If there is more than one possible plan, then the most promising plan should be used for analyzing manufacturability—and thus some plan-based systems generate and evaluate a multitude of plans [23, 24]. The plan-based approach involves reasoning about the processes involved in the product's manufacture.

The direct approach appears to be more useful in domains such as near-net shape manufacturing, and less suitable for machined or electro-mechanical components, in which interactions among manufacturing operations make it difficult to determine the manufacturability of a design directly from the design description. In order to calculate realistic manufacturability ratings for these latter cases, most of the rule-based approaches would require large sets of rules.

3 Product and Manufacturing Resource Models

The information infrastructure of our generative approach includes the Object-Oriented Group Technology (OOGT) representation of the design under consideration and the manufacturing resource models of the candidate partners. The former has been described in Candadai *et al.* [7, 8]. The latter has been discussed by Ramachandran [56]. Both models are briefly overviewed in this section following a description of microwave modules (MWMs).

3.1 Microwave Modules

Many modern telecommunication systems generate, transmit, and receive signals in the 1–20 GHz microwave range; the circuit assemblies that generate, transmit, and receive the microwave signals are termed microwave modules (MWMs).

Modern MWMs include Microwave Integrated Circuits (MICs), in which many functional components of the circuit are fabricated as artwork on the same planar board, using the same fabrication technology. The artwork lies on the dielectric substrate, which is attached to a ground plane that may also serve as a heat sink. In addition to integrated components, which are fabricated as a geometric manifestation of the artwork, MWMs may carry hybrid components, which are assembled separately using techniques such as soldering, wire bonding, and ultrasonic bonding. Mounting these components often requires holes, pockets, and other form features in the substrate.

The processes used in MWM manufacture depend on several factors, including the choice of dielectric material and the degree of integration of functional elements in the design. Common processes include milling, casting, lamination, photomask deposition, etching, plating, adhesive deposition, application of flux, reflow soldering, trimming, cleaning, testing, and tuning [6, 9].

As an example of a MWM, consider the product shown in Figure 2. It has an aluminum clad substrate (Figure 2) that is 7.000 in. long by 3.000 in. wide by 0.250 in. thick and has two holes, two cutouts, and two intersecting pockets. The holes are used for fasteners that secure the board to a housing. The cutouts and pockets are mounting features for three components, including the large capacitor bank shown in Figure 2. These components are connected by the artwork traces. The production quantity is 200. Throughout the paper we will use this sample product to illustrate our generative design evaluation and partner selection approach.

3.2 OOGT Information Model

The product data provided to the generative methods of Sections 4 and 5 are captured by the OOGT product information model, which is a manufacturing view of the product design. This view is inspired by group technology (GT) and includes a composite of two GT codes: 1. The commercial MICLASS GT code [52], which describes the mechanical aspects of the product, including main shape, dimensions, material, and features. 2. A custom code developed in cooperation with Westinghouse Electronic Systems Group, which describes the electrical attributes of an MWM such as electrical classification, components, hardware, and electrical dimensions [7, 8, 26]. Table 1 lists the attributes of both codes. In addition to the GT code, the OOGT information model describes the product material, the production quantity, critical aspects of the geometry and topology of the product envelope, the sub-

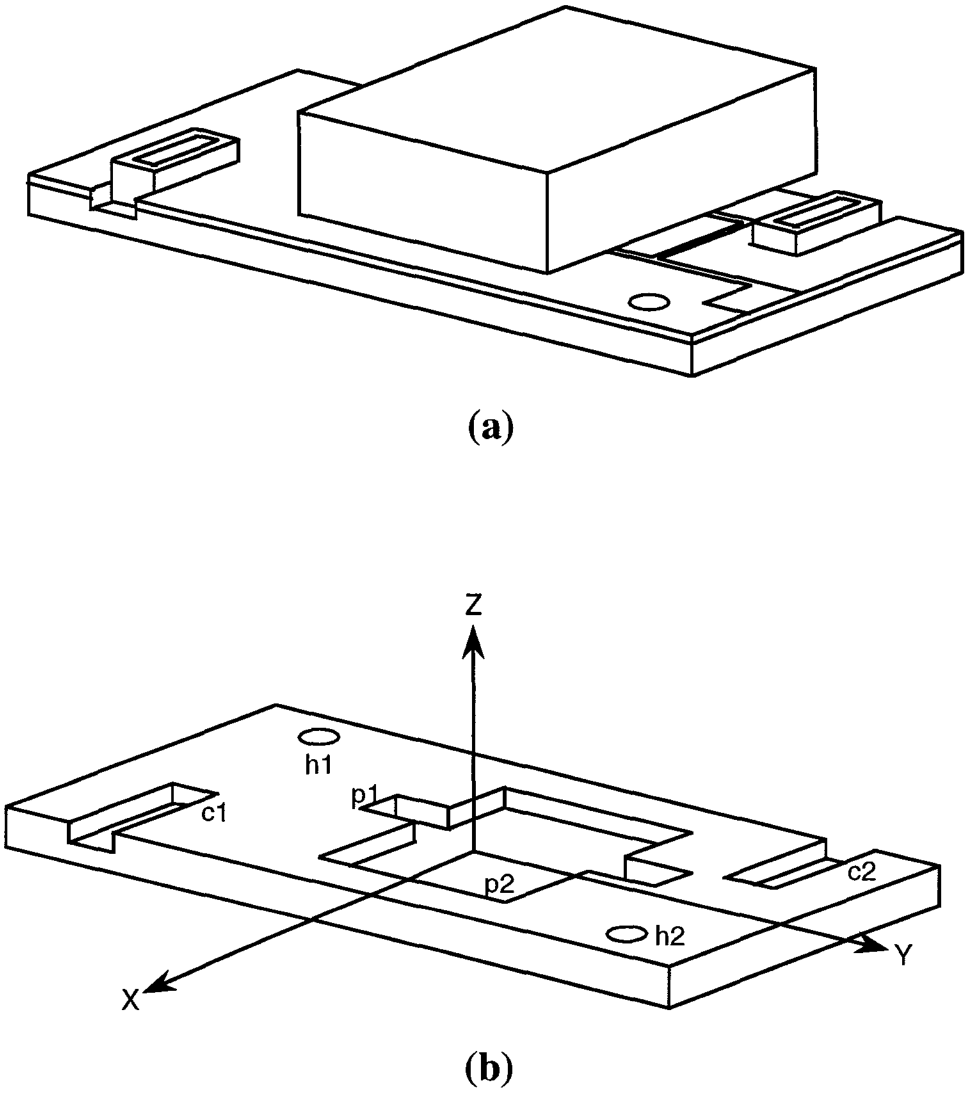

Figure 2: Reference product: (a) assembly, (b) substrate

Table 1: GT coding scheme for flat mechanical parts and MWMs

Digit	MICLASS GT SCHEME	Digit	ELECTRICAL GT SCHEME
1	Main Shape	1	Electrical Classification
2	Machined Cutouts	2-3	Electrical Function
3	Holes Perpendicular to Top Surface	4-5	Component Mounting Methods
4	Machined Secondary Elements	6-7	Component Mounting Patterns
5-6	Mechanical Function	8-9	Non-Soldered Hardware
7-8	Length of the Part	10-11	Soldered Hardware
9-10	Width of the Part	12	Component and Hardware Count
11-12	Thickness of the Part	13	Component Orientation
13	Mechanical Tolerances	14-20	Electrical Dimensions
14-15	Material	21	Qualifying Dimensions
16	Raw Stock Shape	22	Fabrication Tolerances
17	Production Quantity	23	Substrate Type
18	Secondary Element Orientation	24-25	Multiple Platings

strate's form features and their parameters, and the electrical characteristics (see Figure 3). This information is described by appropriate objects, attributes, and methods. Moreover, the model includes additional information critical to evaluating the manufacturability of the design: feature accessibility, feature volume, thin sections, cross section ratios, undercuts, and distance between artwork sections. Candadai *et al.* [7, 8] provide details of the model.

We have developed means that allow the designer to specify the substrate design using a solid modeling design tool, to create the integrated STEP-based product model, and then to generate the corresponding OOGT model for generative design evaluation. The designer first builds an ACIS[1] solid model by specifying the stock dimensions and the form feature parameters. The model-building procedures translate the ACIS solid model into STEP geometric and topological entities which form the product model's boundary representation. In addition, the designer provides supplemental information about the product, the features, and its electrical characteristics; these data form the rest of the product model. The procedures to generate the OOGT attribute values are of two types: Direct mapping procedures generate GT digits and OOGT objects directly from the information captured in the product model. Indirect mapping procedures first determine design attributes by reasoning about the product design. Subsequently, these procedures map the derived attribute values to the corresponding GT digits or OOGT objects (see [8] for details).

[1]ACIS is a commercial solid modeling kernel that provides capabilities for constructing and analyzing solid models [69].

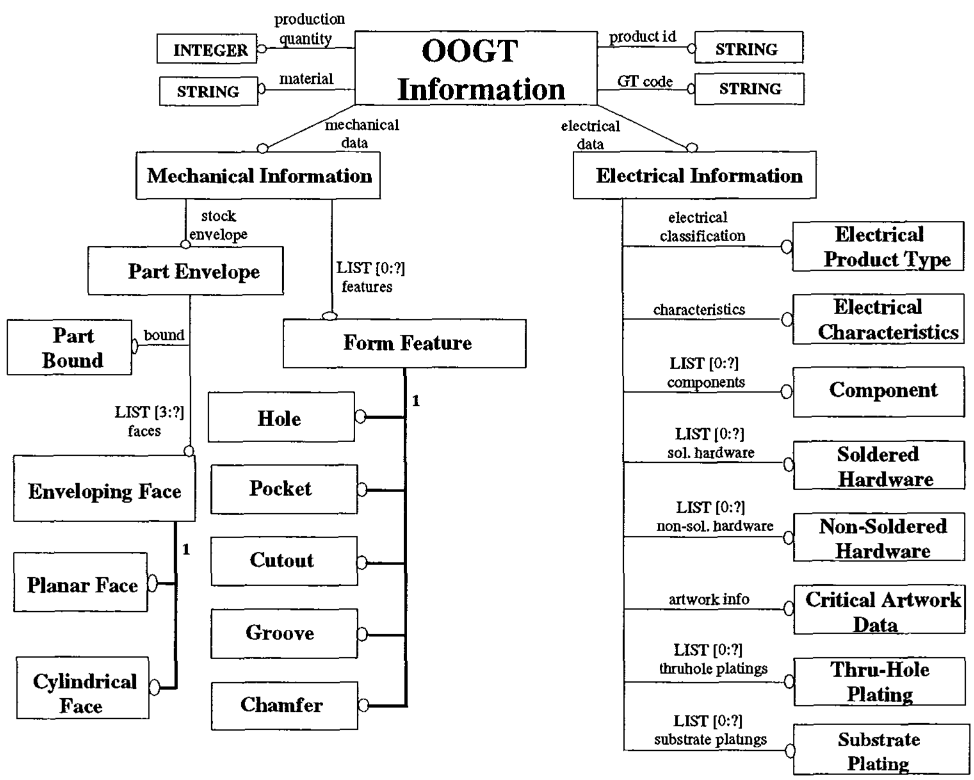

Figure 3: Overview of the OOGT information model in EXPRESS-G

3.3 Manufacturing Resource Model

We have developed a new manufacturing resource model to capture general information about a firm and the manufacturing capabilities and performance of its factories. Major sources used during model development include previous work on supplier selection (see Section 2) and significant input from designers and manufacturing engineers from Westinghouse, Lockheed-Martin, and the U.S. Army Tank-Automotive Command. The model was developed in the modeling language EXPRESS [34] and is fully described by Ramachandran [56].

The base model entity is *manufacturing firm*, which describes the partner's financial information and customer-related data. A *manufacturing firm* has a list of one or more *manufacturing plants.* The entity *manufacturing plant* describes the general performance and attributes of a plant. The model adopts a logical partition of the plant's information into three groups: manufacturing management systems, engineering systems, and manufacturing processes. Note that this is simply a view of a potential partner and need not indicate the actual organizational structure of the partner firm. The following paragraphs overview those entities that are relevant to two basic functions of agile manufacturing: partner prequalification and partner evaluation (with respect to the requirements of a candidate design).

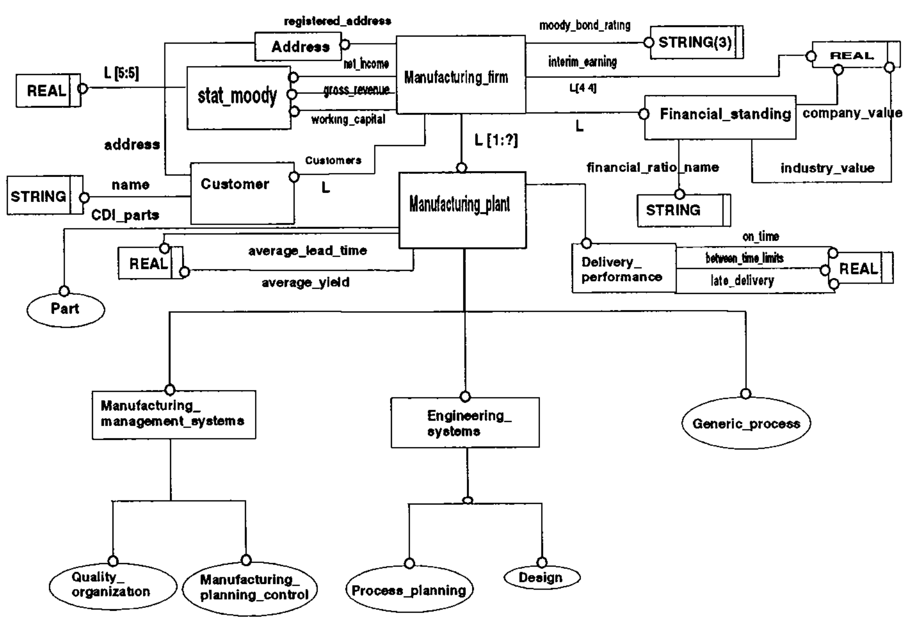

Figure 4: Overview of the manufacturing resource model. Each box represents an entity in the model. Thick lines represent subtype relationships, and thin lines represent attribute relationships. Note that a subtype (child) of an entity (parent) inherits all the attributes and behavior from the parent and may also include additional attributes and behavior.

Prequalification Information The model has the following types of prequalification information: financial strength and customer information, quality and manufacturing management systems, engineering systems, and product lines. The financial strength is described, in the entity *manufacturing firm*, by data from Moody's handbook of common stock [47]. This entity also lists the firm's customer base. The entity *quality organization* contains information about the quality-related business processes in each manufacturing plant. This information is organized into different entities according to the ISO 9000 standard [32]. The entity *manufacturing planning and control* describes the manufacturing management systems, including inventory control policies, MRP II, production activity control methods, and other related practices. The *engineering systems* entities describe procedures followed during product design and process planning. Finally, the manufacturing resource model includes a concise description of the product line of a plant. The Object-Oriented Group Technology model has been employed as a product descriptor.

Manufacturing Capabilities and Performance Determining if a potential partner can realize some portion of a new product design requires information about that plant's manufacturing process capabilities, which can be described using different levels of aggregation. Evaluating a product design's plant-specific manufacturability requires process performance data, which also occur at different levels.

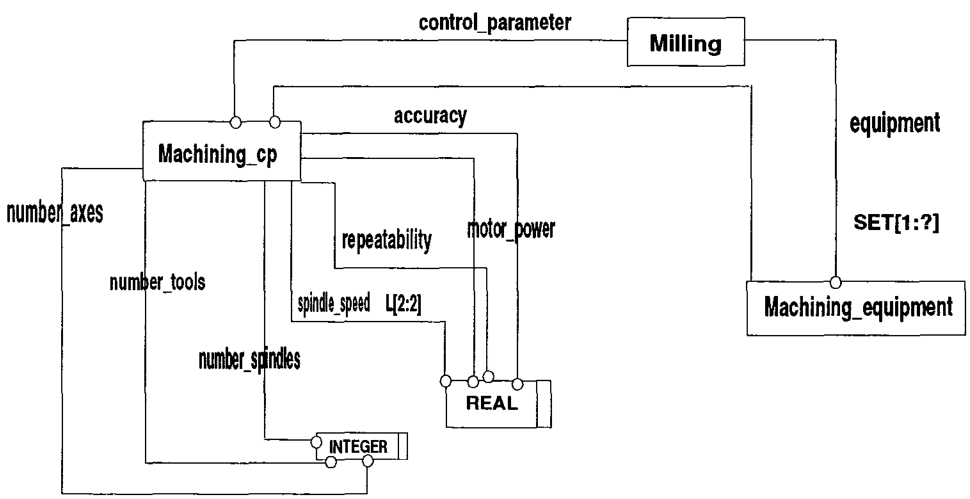

Figure 5: Modeling of milling subprocess

The entity *generic process* captures information related to a manufacturing process. Each process has a list of related *subprocesses.* Each subprocess has a set of critical process parameters used to describe its manufacturing capabilities.

Process capability data exist at two levels: the subprocess level and the individual equipment level. The data at the subprocess level aggregate the best capabilities of the available equipment. For example, consider an instance of the *process* "machining." It has a list of

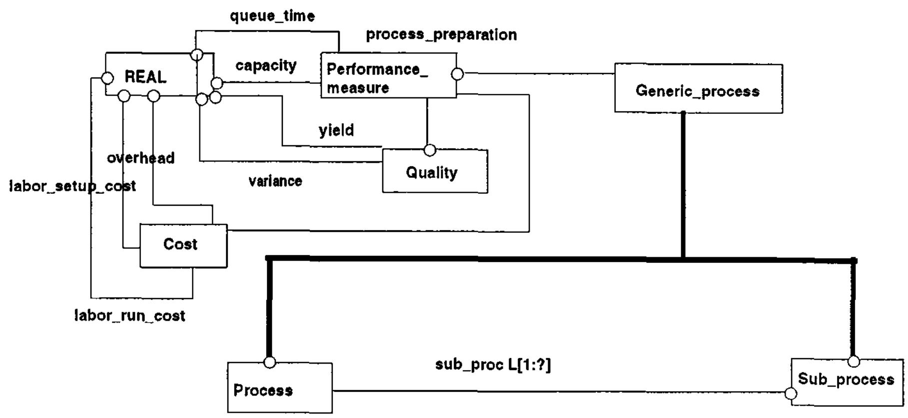

Figure 6: Process representation structure

associated *subprocesses*, which may be *milling*, *turning*, and *drilling*. *Turning* has a list of critical process parameters, such as spindle motor power and axes travel, and a list of lathes. The description of the process parameters of a lathe has a structure identical to the process parameters of the turning *subprocess*. The values of the process parameters for each lathe express its capabilities. Figure 5 shows the process capability model for milling.

In addition to the description of the process capabilities, the performance of each *process*, *subprocess*, and *equipment* is described by an entity *performance measure*, which has the following attributes (see also Figure 6): quality (cumulative yield or process variance), cost rate (setup cost, run cost, and overhead rates), lead time (average queue time and company-specific process preparation time), and capacity (in hours per day).

4 Feasibility Assessment

To evaluate the feasibility of manufacturing (portions of) the design in each of a universe of candidate partners we perform high-level process planning. The feasibility assessment process generates alternative plans for manufacturing the design and provides feedback to the designer on possible infeasibilities.

4.1 Process Planning Data Structure

In distributed manufacturing it is important to enlarge the feasible manufacturing space in order to determine the most favorable set of processes and plants to manufacture the product. We represent these alternatives systematically in a special process planning data

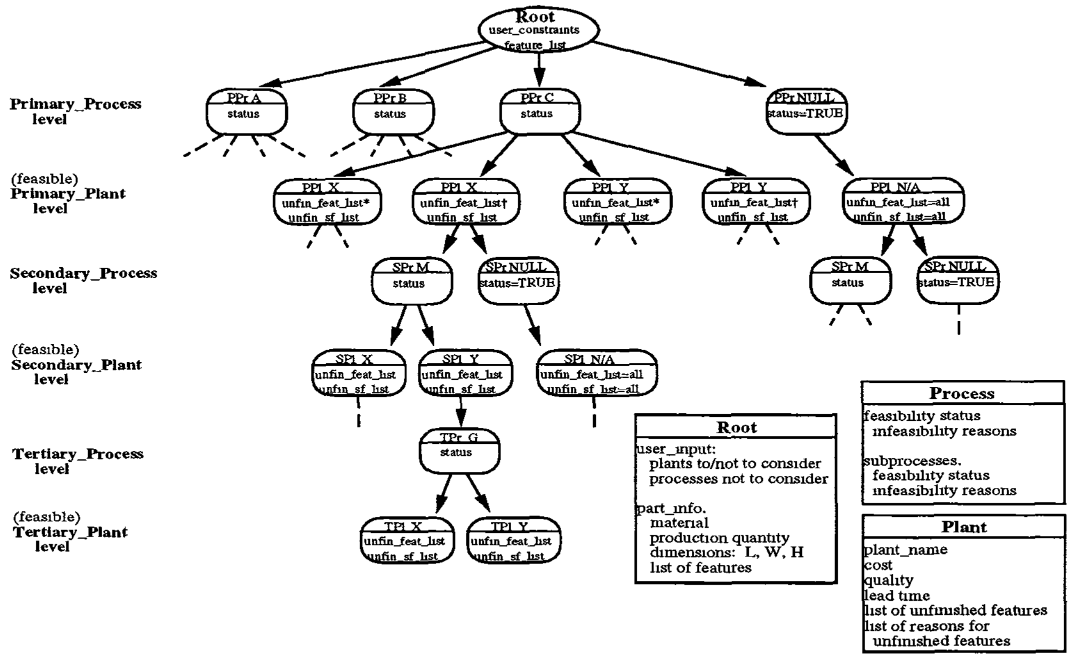

Figure 7: Process plan data structure (PPDS) for mechanical parts.

structure (PPDS), which also captures information about the process steps, their sequence, and the plants that perform these steps.

The structure of the PPDS for mechanical parts is based on the classical taxonomy of manufacturing processes into primary, secondary, and tertiary processes. Primary processes are net-shape processes such as casting, forging, and injection molding. Secondary processes are material removal processes, which generate the product features, such as machining and electro-discharge machining (EDM). Tertiary processes are finishing operations, which do not affect product geometry significantly, such as grinding, reaming, and lapping. Some processes such as machining and grinding are composed of subprocesses; e.g., drilling and milling are subprocesses of machining, and surface grinding and internal grinding are subprocesses of grinding.

For the manufacture of the electromechanical products considered in this study, there are limited processing alternatives, and thus the corresponding PPDS is also limited. For MWMs, high-level process plans include five processing steps. The first two steps, which are used to drill and plate conductive holes and machine all features of the MWM substrate, include through-hole plating and machining. These two steps can be performed in two alternative sequences: machining followed by through-hole plating, or drilling and through-hole plating followed by machining. The remaining processing steps are artwork generation, which includes substrate etching and plating; automated or manual component assembly and soldering; and testing. For mechanical products, however, there is a large set of primary, secondary, and tertiary processes. In our work we have considered investment casting, sand casting, forging, milling, drilling, internal grinding, and surface grinding.

The PPDS uses three classes of objects: a root node, process nodes, and plant nodes. The root node contains information about the product as well as user-specified process planning constraints. Process nodes and plant nodes represent the processes and plants that may be used to manufacture the design, respectively. Following the root node, process and plant nodes are organized into alternating levels as shown in Figure 7. NULL nodes are used to represent the absence of a process.

In the PPDS of Figure 7, each leaf corresponds to a feasible high-level process plan or an infeasible alternative. The process nodes describe the feasibility of manufacturing a portion of the design using that process (or the associated subprocesses) regardless of plant-specific capabilities. Each process node contains a feasibility flag, a list of possible causes for infeasibilities, and a list of pointers to candidate plants. The feasibility flag indicates whether the process is globally infeasible for the design under consideration; i.e., it is infeasible at any plant. In this case, the causes for infeasibility are captured in the corresponding list. The plant nodes describe the feasibility of manufacturing a portion of the design at a particular plant using the process (or associated subprocesses) of the parent (process) node. Each plant node contains a list of unfinished features, a list of features with unsatisfied surface finish requirements, a list of pointers to subsequent process alternatives, and three manufacturability attributes: lead time, cost, and quality. Each unfinished feature is either infeasible or unpreferable to manufacture in the plant under consideration [39]. For each unfinished feature, a list of infeasibility causes is maintained. These causes are plant-specific. For example, a machining plant node may have an infeasible feature because the accuracy of the plant's machining processes does not satisfy the feature's tolerance requirements.

In summary, the combination of a feasible process node and a feasible plant node represents a complete processing step in a high-level process plan: it describes the operations performed at the manufacturing plant and the remaining features which need to be manufactured by subsequent steps.

4.2 High-level process planning methods

The high-level process planning approach generates feasible process alternatives at each step by process selection and plant selection. Process selection is a plant-independent procedure which retrieves all candidate processes associated with key design attributes and discards processes which are globally infeasible (infeasible at any plant). Given a candidate process, plant selection uses manufacturing capability data (from the manufacturing resource models) and product characteristics to identify the manufacturing plants that can perform this process.

Generic process knowledge is necessary for high-level process planning. This knowledge, typically found in manufacturing handbooks, describes universal process capabilities, material-process compatibilities, and recommended production quantities. We have organized such data in a simple process information model. Table 2 shows a representative table

from this model, which was populated with data from various sources including design handbooks [5, 10, 68], manufacturing handbooks [12, 16, 30, 73], and materials handbooks [18]. Table 2 shows the compatible material-process combinations, compatible feature-process combinations, and global process attributes such as recommended production quantities.

Process Selection

Process selection uses process-specific rules to identify, based on the product characteristics, potentially feasible processes and to discard processes which are globally infeasible (infeasible at any plant). Process feasibility within a candidate plant is considered in the plant selection step. Below we summarize the process selection rules, which Lam [39] describes in detail.

- For primary mechanical processes, we use the product material to identify candidate processes. For each cnadidate process we compare the recommended production quantity to the desired production quantity (see Table 2).

- The only mechanical secondary process considered is milling and its subprocesses. Holes require drilling; other features such as pockets, cutouts, and grooves require milling. The candidate subprocess for a feature is feasible only if the feature is accessible by a cutting tool and has a depth to minimum profile dimension ratio less than a certain value. Other feasibility checks are performed when examining production feasibility within a candidate plant.

- The tertiary mechanical process considered is grinding and its subprocesses. Surface finishing of features requires internal grinding, while surface finishing of other surfaces requires surface grinding (since we consider parts with prismatic envelopes). Internal grinding is feasible only if each associated feature is accessible and has a depth to minimum profile dimension ratio within a certain range.

- For microwave modules, which have a clad substrate and an insulation layer that regular milling would tear, high-speed milling is selected to create the features of the substrate; milling feasibility is assessed as discussed above.

- For microwave modules, if plated through-holes are present, we select both drilling and plating. Drilling feasibility is evaluated as discussed above. Plating is globally feasible [12].

- Artwork generation includes etching and substrate plating subprocesses, which are globally feasible [12].

- If the product has hybrid components, it requires assembly, which includes automated or manual mounting and soldering steps. If the production quantity is greater than 100 units and the product has surface mount components, we choose automated assembly. For a small production quantity or through-hole mount components, we choose manual assembly. Both processes are globally feasible.

- Finally, a microwave module requires testing, which is globally feasible. (The availability of required resources is examined in plant selection.)

processes	selected materials										features					other attributes			
	aluminum	brass	copper	cast iron	carbon steel	tungsten	LDPE	HDPE	nylon	PEEK	hole	pocket	cutout	chamfer	groove	smallest env.: dimension (in)	largest env. dimension (in)	lower qty bound.	upper qty. bound
die casting	•		•								•	•	•	•	•	1.25	12	1000	99000
inv. casting	•		•								•	•	•	•	•	1.00	25	1000	99000
sand casting	•	•	•	•	•						•	•	•	•	•	1.25	20	1	100000
forging	•	•	•		•	•					•	•	•	•	•	0.50	1000	2500	25000
inj. molding							•	•	•	•	•	•	•	•	•	0.035	50	7500	99000
milling	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	0.25	100	1	250
drilling	•	•	•	•	•	•	•	•	•	•	•					0.25	100	1	250
int. grinding	•	•	•	•	•	•	•	•	•	•	•					1.00	25	1	250
sf. grinding	•	•	•	•	•	•	•	•	•	•				•		0.25	100	1	250

Table 2: Sample table of the process information model.

Plant Selection

Plant selection uses plant information from the manufacturing resource model to identify which candidate partners are capable of using, in the manufacture of the candidate design, the process identified by process selection. In general, a globally feasible process is feasible at a candidate partner plant if the process is available at the plant and the plant's capabilities satisfy the design requirements. If a process or plant is infeasible, the PPDS stores the cause(s) of infeasibility. Using this information, the designer may modify the product design appropriately. For each globally feasible process and each candidate plant, the plant selection approach creates, if necessary, two plant nodes in the PPDS: the first corresponds to the manufacturing attributes (e.g. features) that the plant can feasibly create using the process under consideration, and the second corresponds to the preferable attributes. A preferable attribute (or feature) is easy to manufacture with the plant's resources. We use process-specific rules to exclude certain feasible features from the set of preferable features. For example, a casting feature is infeasible if it causes a minimum section thickness less than 0.150 in. or a section thickness change ratio greater than 4. A feasible feature is preferable if the corresponding minimum section thickness is greater than 0.250 in. This approach thus increases the number of manufacturing alternatives that the designer can consider. Below we summarize the plant selection rules, which Lam [39] describes in detail. These rules require product data from the OOGT model and process capability data from the manufacturing resource model.

- For a primary process, the process in a candidate plant must be able to accommodate the product envelope size. For casting processes, a feature is infeasible if it causes a minimum section thickness less than 0.150 in. or a maximum section thickness change ratio greater than 4. A feasible feature is preferable if the minimum section thickness is greater than 0.250 in. For forging and injection molding processes, the feature feasibility rules consider the minimum section thickness, the maximum section change

Table 3: Surface finish capability of selected processes.

Process	*Surface finish capability (μin)*
Ceramic Mold Casting	31
Die Casting	16
Investment Casting	16
Pressure Die Casting	31
Sand Casting	248
Forging	63
Injection Molding	8
Milling & Drilling	4
Grinding	1

ratio, and whether the feature causes an undercut in a certain direction. Note that the necessary feature related attributes (such as minimum section thickness, maximum section thickness change ratio, and undercut directions) are provided to the rules by the OOGT model and have been derived from the STEP model during automated OOGT processing (see Candadai *et al.* [8]). The primary process may also achieve certain surface finish values, which are provided in Table 3.

- For a secondary process, the machining subprocess in a candidate plant should be able to achieve the required placement and dimensional tolerances of features. Our approach does not consider geometric tolerances. We consider the achievable placement tolerance to be equal to the machine tool accuracy. The achievable dimensional tolerance depends upon the machine tool condition (high- or low-precision). In our approach, a machine is considered to be low-precision if its accuracy is lower than the average handbook value for accuracy of similar machines [5]; otherwise the machine is considered to be high-precision. Thus, the one-sided achievable dimensional tolerance τ is determined in the following manner using the machine accuracy a_m and the average handbook value a_h of accuracy for similar machines: For low-precision machines, $\tau = 0.8a_m + 0.2a_h$. For high-precision machines, $\tau = 0.2a_m + 0.8a_h$. Table 3 provides the achievable surface finish values of the machining subprocesses.

- Tertiary processes in a candidate plant must be able to achieve the surface finish specifications that the primary and secondary processes were unable to meet. The achievable surface finish s depends upon the grinding machine, its accuracy s_m and the handbook value s_h for similar machines: For a low-precision machine, $s = 0.8s_m + 0.2s_h$. For a high-precision machine, $s = 0.2s_m + 0.8s_h$.

- A plating process in a candidate plant must be able to achieve the required plating thickness and accommodate the product envelope size.

- An etching process in a candidate plant must be able to achieve the required line width tolerance and line spacing tolerance.

Table 4: Design specifications for the MWM.

OOGT Product Model Data	
Material	Aluminum Clad
Production Quantity	200
Envelope length	7.000 in.
Envelope width	3.000 in.
Envelope height	0.250 in.
Tightest dimensional tol. req.	± 0.001 in.
Etching line width tol. req.	± 0.005 in.
Etching line spacing tol. req.	± 0.005 in.
Etching thickness	0.001 in.
Plating thickness	0.0001 in.

- A manual assembly or soldering process in a candidate plant must include the necessary resources; no other feasibility criteria exist. An automated assembly process must be able to achieve the required component placement tolerance.
- A testing process is locally feasible if the plant has all required testing equipment for MWMs, which include pulse generators, signal generators, wave analyzers, power meters, and power supplies.

4.3 Example

Consider a customer order for 200 units of the sample product described in Section 3.1 and shown in Figure 2.

It is assumed that the product's aluminum substrate has already been clad with the required teflon dielectric layer. Table 4 lists those design attributes which are related to the MWM envelope and tolerances. The substrate has six features that are described by the attributes listed in Table 5. (The volume of feature p_1 and the volume of feature p_2 equals half of the combined pocket volume.) In addition, the MWM has three components, which are described by the attributes listed in Table 6. The two through-holes are used for mounting the module assembly onto a rack assembly and thus do not require through hole plating. Cutouts $c1$ and $c2$ are needed to fit components e_1 and e_2. The two blind pockets in the center of the substrate are used as reliefs for the capacitor bank pm_1, which must be mounted with a placement tolerance of 0.005 in. All data are captured in the product's OOGT model and have been generated from the STEP-based product model using the techniques described by Candadai *et al.* [8].

Consider three potential partners; Tables 7 and 8 include critical process capability and

Table 5: Feature attributes from the OOGT product model

feature	h1	h2	c1	c2	p1	p2
accessibility	OK	OK	OK	OK	OK	OK
L/D ratio	0.50	0.50	0.50	0.50	0.50	0.12
dimensional tolerance (in)	$\pm$ 0.001	$\pm$ 0.001	$\pm$ 0.001	$\pm$ 0.001	$\pm$ 0.001	$\pm$ 0.001
min. section thickness (in)	0.020	0.020	0.050	0.050	0.050	0.050
maximum abrupt section change ratio	3	3	2	2	2	2
undercut directions	x, y	x, y	y	y	x, y	x, y
volume (in^3)	0.0123	0.0123	0.125	0.125	0.375	0.375
min. profile dimension (in)	0.25	0.25	0.25	0.25	0.25	2.00
corner radius			0.0625	0.0625	0.0625	0.0625

Table 6: MWM component attributes

component	placement tolerance	mounting method
power module pm_1	0.005 in.	std. surface mount–no solder
component e_1	0.005 in.	non-std.–epoxy
component e_2	0.005 in.	non-std.–epoxy

Table 7: Relevant manufacturing plant data for Plant B

	Plant B
overhead rate (%)	185
setup labor rate ($/hr)	20
run labor rate ($/hr)	20
Machining	
Milling Accuracy (in.)	0.0005
Drilling Accuracy (in.)	0.0005
queue time (hrs)	4.0
process preparation time (hrs)	0.5
Milling σ (in.)	0.00045
Drilling σ (in.)	0.00045

performance data obtained from the corresponding manufacturing resource models. As shown in Table 7, Plant B has machining facilities and will be considered for machining the six features of the MWM's substrate. Plants C and D have electrical process capabilities for artwork production, component assembly, and MWM testing, as shown in Table 8.

The following paragraphs describe the generation of high-level process plans.

Machining process/plant selection

The first and second levels of the PPDS are populated with a NULL process and a NULL plant node, respectively, to indicate that through-hole plating is not required. All machining features are unfinished in the NULL plant node.

All features are feasible for milling and drilling, since they are accessible and have acceptable depth to minimum profile dimension ratios (L/D ratios). Furthermore, Plant B is the only plant capable of machining the features to tolerance, since its high-accuracy machines have an achievable dimensional tolerance $\tau = 0.2a_m + 0.8a_h = 0.2(0.0005) + 0.8(0.001) = 0.0009$ in., which is less than the required dimensional tolerance of ± 0.001 in. Therefore a machining process node and a machining plant node are added to the PPDS for Plant B. All features are machined at this point, and the unfinished feature list is empty.

Artwork generation process/plant selection

An artwork generation process node is inserted in the PPDS and includes etching and plating subprocesses. Table 9 is a checklist of the plant evaluation criteria. The table lists the design requirements as well as the capabilities of Plant C and of Plant D. The checklist indicates that both Plant C and Plant D are capable of etching and plating the MWM artwork. Thus artwork generation plant nodes are added to the PPDS representing both plants.

Assembly process/plant selection

Table 8: Relevant manufacturing plant data for Plants C and D

overhead rate (%)	150	140
setup labor rate ($/hr)	25	30
run labor rate ($/hr)	25	30
Artwork Generation		
Etching line width tolerance capability (in.)	±0.0005	±0.001
Etching line spacing tolerance capability (in.)	±0.0005	±0.001
Achievable plating thickness (in.)	0.01	0.015
Max. plating part envelope dimension (in.)	30	17.5
queue time (hrs)	3.0	21.0
process preparation time (hrs)	0.5	2.0
Etching σ (in.)	0.0015	0.00125
Plating σ (in.)	0.0015	0.002
Assembly and Soldering		
Automated assembly placement accuracy (in.)	0.003	0.003
queue time (hrs)	4.0	12.0
process preparation time (hrs)	0.5	2.0
Automated assembly rate (comp/hr)	90	150
Manual assembly rate (comp/hr)	60	50
Automated assembly σ (in.)	0.001	0.00045
Manual assembly yield (%)	85	95
Testing		
queue time (hrs)	4.0	
process preparation time (hrs)	0.5	

Table 9: Artwork generation checklist

Criteria	Required (inches)	Plant C Capabilities (inches)	Plant D Capabilities (inches)	Feasible Plants
Etching line width tolerance	±0.005	±0.0005	±0.001	C, D
Etching line spacing tolerance	±0.005	±0.0005	±0.001	C, D
Plating thickness	0.0001	0.010	0.015	C, D
Longest env. dimension	7.000	30.00	17.50	C, D

Table 10: Four process plans

Process Step	Process Plan λ_1	Process Plan λ_2	Process Plan λ_3	Process Plan λ_4
Machining	Plant B	Plant B	Plant B	Plant B
Artwork generation	Plant C	Plant C	Plant D	Plant D
Assembly	Plant C	Plant D	Plant C	Plant D
Testing	Plant C	Plant C	Plant C	Plant C

Automated assembly and soldering are considered for MWMs with surface mount components and production quantities greater than 100 parts. Manual assembly and soldering are considered for non-surface mount components, which are infeasible for automated assembly and soldering. Since the production quantity in this example is 200 and automated assembly is a candidate subprocess for mounting, component pm_1 is surface mounted automatically. Components c_1 and c_2 are non-standard epoxy mounted components and thus, are mounted manually. An assembly process node is inserted into the PPDS with automated assembly and manual assembly as subprocesses.

Assembly plant evaluation compares the achievable and required component placement tolerances. The value of the achievable placement tolerance from Table 8 is 0.003 in. while the required placement tolerance from Table 6 is 0.005 in. Thus, automated assembly is feasible for component pm_1. Manual assembly is always feasible. A plant node is inserted into the PPDS for assembly at Plant C. All features are finished and all components have been mounted. Because Plant D can also achieve this placement tolerance, a plant node is inserted into the PPDS for assembly at Plant D.

Testing process/plant selection

Testing and tuning is a manual process that is feasible if the plant has the necessary equipment. Plant C has the facilities for MWM testing and tuning, and a process and plant node are added to the PPDS to complete the process plan. Plant D does not have the facilities for MWM testing and tuning.

The final process planning data structure is shown in Figure 8. Given the set of potential partners shown in Tables 7 and 8, there are four feasible high-level, plant-specific process plans. Table 10 shows the processes and plants involved in these plans.

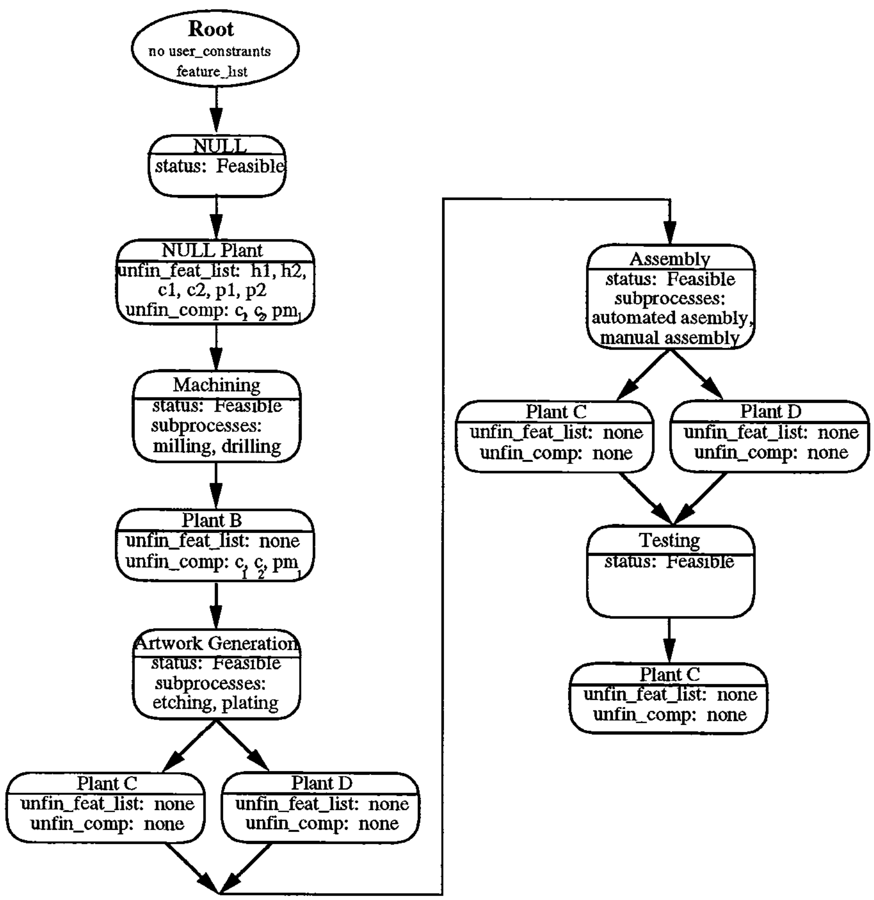

Figure 8: Final PPDS for MWM assembly

5 Plan-Based Design Evaluation

Following high-level process planning, manufacturability analysis is performed to evaluate the feasible process plans and to determine the difficulty of manufacturing the design by alternative sets of partners. The manufacturability is quantified in terms of manufacturing lead time, cost, and quality. Note that lead time is the manufacturing lead time, not the total lead time that spans the period between order placement and delivery; the cost is the production cost and does not include material and shipping costs. The design evaluation provides the designer with feedback on the factors that affect the overall cost, quality, and lead time of the product design. With this information, the designer can modify the design to improve its manufacturability with respect to the specific manufacturing plants that will realize the proposed design.

5.1 Design Evaluation Approach

In order to determine the lead time, cost, and quality for each high-level process plan, we determine the lead time, cost, and quality of each process-plant combination and combine the results accordingly. That is, the total lead time, production cost, and estimated plan quality are given by the following equations:

$$T(\alpha, \lambda) = \sum_{j \in \lambda} t_j(\alpha)$$

$$C(\alpha, \lambda) = \sum_{j \in \lambda} c_j(\alpha)$$

$$Y(\alpha, \lambda) = \prod_{j \in \lambda} y_j(\alpha)$$

where design α is manufactured by high-level process plan λ; $t_j(\alpha)$, $c_j(\alpha)$, and $y_j(\alpha)$ are the lead time, cost, and yield, respectively, associated with each process-plant combination j (which belongs to the high-level process plan λ) for the manufacture of design α.

To determine the above manufacturability measures for a process-plant combination, we require information about the product design and the manufacturing plant performing the process. The OOGT model supplies the necessary product data such as material, feature volume, etching thickness, etc. The manufacturing resource model supplies the necessary data about manufacturing performance such as queue time, process variation, etc. Process-specific parameters and knowledge are encoded in the manufacturability assessment rules used in this approach. Since the high-level process plan does not include process parameter data, typical parameter values are found from the process information model (see Section 4.2 and [5, 10, 12, 41, 68]). The manufacturability assessment procedure searches the entire PPDS, calculates the lead time, cost, and quality of each feasible process-plant combination, and stores those measures in the corresponding plant node.

The following discussion describes the general formulas used for each measure. Through the example of Section 5.2, we illustrate the specific equations used for some of the processes. These equations use the product data, manufacturing capabilities and performance data, and manufacturing process parameters mentioned above. For a complete description of our methods see Lam [39] and Minis [42].

Lead Time $t_j(\alpha)$

The lead time for an individual process is the sum of the processing time and the idle time. Processing time includes the recurring setup and run times. Idle time includes queue time and process preparation time (non-recurring setup time). It is emphasized that these plant-specific idle times may comprise a significant portion of the total manufacturing lead time (e.g. 80%-90% [67]). Thus, the total lead time $t_j(\alpha)$ for a process-plant combination j in the high-level process plan λ for design α is given by:

$$t_j(\alpha) = \theta_j^q + \theta_j^s + \theta_j^r(\alpha) \tag{1}$$

where θ_j^q, θ_j^s, and $\theta_j^r(\alpha)$ are the corresponding queue time, process preparation time, and processing time, respectively. The values of θ_j^q and θ_j^s are design-independent, are approximated by the historical averages for the process in the plant under consideration, and are provided by the plant resource model.

The processing time $\theta_j^r(\alpha)$ depends on the design α and is the product of the lot size and the sum of the recurring setup and run times. Note that since process yields are generally less than 100%, the plant will have to rework some parts to output the desired production quantity. In our approach, the effective lot size N_j for each process-plant combination j is:

$$N_j = \frac{N_o}{y_j(\alpha)} \tag{2}$$

where N_o is the desired production quantity obtained from the OOGT product model and $y_j(\alpha)$ is the yield of the process-plant combination j. This effective lot size N_j is used to adjust the total setup and run times in order to account for rework. Note that we make the simplifying assumption that no scrap is generated by each process-plant combination, which starts with N_o parts and outputs the N_o parts that the next process needs.

Lam [39] presents the procedures for determining $\theta_j^r(\alpha)$ for each process. The processes considered include investment casting, sand casting, forging, milling, drilling, internal grinding, surface grinding, etching, plating, automated assembly, automated soldering, manual assembly and soldering, and electrical testing. We validated our time estimation procedures by comparing them with similar procedures in the literature (wherever prossible). As an example, consider Figure 9, which compares the cost of forging, expressed as a function of production quantity, to the ICAM results for forging [50]. ICAM is a manufacturing cost design guide for aerospace parts. It uses empirically validated rules and formulas to estimate manufacturing cost given basic design information.

Further examples of these time estimation procedures are given in the next section.

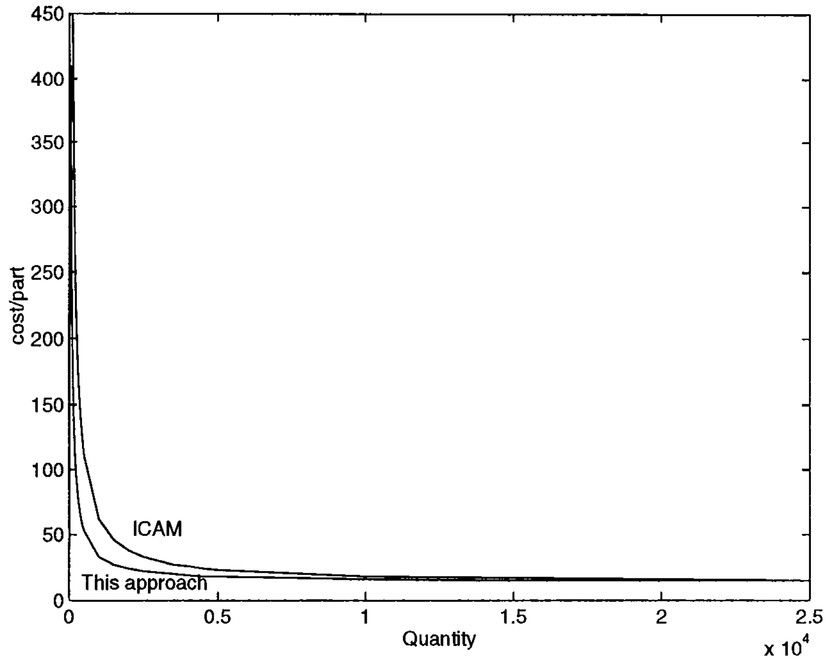

Figure 9: Forging cost comparison

Manufacturing Cost $c_j(\alpha)$

The cost of a process-plant combination j in plan λ for design α depends on the process preparation time θ_j^s, the operator time $\theta_j^o(\alpha)$ and the cost rates of the manufacturing plant under consideration. These rates include the process preparation labor rate ρ_j^s, processing labor rate ρ_j^r, and overhead rate ρ_j^h. The manufacturing cost $c_j(\alpha)$ is evaluated by the following equation:

$$c_j(\alpha) = (1 + \rho_j^h)[\rho_j^s\theta_j^s + \rho_j^r\theta_j^o(\alpha)] \tag{3}$$

The three rates ρ_j^h, ρ_j^s, and ρ_j^r are plant-specific and are retrieved from the plant's manufacturing resource model.

Quality $y_j(\alpha)$

Two alternative measures are used to quantify the product quality obtained from a process-plant combination: process yield $y_j(\alpha)$ or process capability ratio $C_{p(j)}(\alpha)$. For processes such as machining, grinding, automated assembly, or etching,

$$C_{p(j)}(\alpha) = \frac{\Delta_\alpha}{6\sigma_j}$$

where Δ_α is the width of the *tightest* tolerance range in the design α and is obtained from the OOGT product model; σ_j is determined from the process variance σ_j^2 available in the manufacturing resource model of the plant. For some processes such as casting, forging, manual assembly, and testing, quality is described by yield. In this case, we use the historical yield y_j of the process-plant combination j which is captured in the manufacturing resource model of the plant.

In order to determine the cumulative quality rating for a high-level process plan, all process capability ratios are converted to yields by using the normal distribution table. The resulting yield values are used to calculate the effective lot size for the process (Equation 2) and the estimated plan quality for a complete high-level process plan.

5.2 Example

In this section, we evaluate the cost, quality, and manufacturing lead time of the alternative high-level process plans λ_1, λ_2, λ_3, and λ_4 that we created in Section 4.3.

Quality

The estimated plan quality, which is measured as a yield, includes the machining yield at Plant B, the artwork generation yield at Plant C or D, the assembly yield at Plant C or D, and the testing yield at Plant C. The yield values $y_j(\alpha)$ for each process-plant combination j in the PPDS are listed in Table 11. The calculation of these yields is described below. Recall that these yields allow us to estimate the additional effort required for rework; thus they affect process cost.

The milling process capability ratio $C^m_{p(B)}(\alpha)$ and the drilling process capability ratio $C^d_{p(B)}(\alpha)$ are given by

$$C^m_{p(B)}(\alpha) = \frac{\Delta^m_\alpha}{6\sigma^m_B} = \frac{0.002}{6 * 0.00045} = 0.7407 \tag{4}$$

and

$$C^d_{p(B)}(\alpha) = \frac{\Delta^d_\alpha}{6\sigma^d_B} = \frac{0.002}{6 * 0.00045} = 0.7407 \tag{5}$$

In the above relationships, the superscript m denotes milling and the superscript d denotes drilling. The tightest tolerance range of 0.002 is obtained by the OOGT model. The manufacturing resource model for Plant B provides the process standard deviations of 0.00045. A process capability ratio of 0.7407 translates to a yield of 97.37%; thus, the machining yield is $(0.9737)(0.9737) = 0.9482$.

The artwork generation yield for Plant C is determined by calculating the etching and plating process capability ratios using the approach described above, converting them to yields, and multiplying the yield values to provide a cumulative value of 81.80%. The artwork generation yield for Plant D is 75.28%. The assembly yield for Plant C is found by evaluating the process capability ratio for automated assembly, converting it to a yield, and taking the product of the automated assembly yield and the manual assembly yield (which is given in Table 8) to get 83.94%. The assembly yield for Plant D is 95.00%.

Lead Time

The total lead time includes the machining lead time at Plant B, the artwork generation

Table 11: Process Yields

Process & Plant	Yield
machining at Plant B	94.82%
artwork generation at Plant C	81.80%
artwork generation at Plant D	75.28%
assembly at Plant C	83.94%
assembly at Plant D	95.00%

lead time at Plant C or D, the assembly lead time at Plant C or D, and the testing lead time at Plant C. These lead times are evaluated below.

According to the manufacturability procedures described by Lam [39], the machining lead time $t_B^m(\alpha)$ at Plant B is the sum of the queue time, the process preparation time, the milling time, and the drilling time

$$\begin{aligned} t_B^m(\alpha) &= \theta_B^q + \theta_B^s + [\tau_B^{ms}(\alpha) + \tau_B^{mx}(\alpha) + \tau_B^{mm}(\alpha)]N_{Bm} \\ &\quad + [\tau_B^{ds}(\alpha) + \tau_B^{dx}(\alpha) + \tau_B^{dm}(\alpha)]N_{Bd} \end{aligned} \tag{6}$$

where θ_B^q and θ_B^s are the machining queue and process preparation times, which are obtained from Table 8. $\theta_B^q = 4$ hrs is the machining queue time of Plant B; $\theta_B^s = 0.5$ hrs is the non-recurring machining setup time at Plant B. The remaining values are calculated as follows.

$\tau_B^{ms}(\alpha)$ is the recurring setup time for milling; $\tau_B^{ds}(\alpha)$ is the recurring setup time for drilling. For Plant B, both times are 18.6 secs per part and are computed as follows: for this part's weight (a function of the volume and material), the handling time given by Boothroyd *et al.* [4] is 18.6 secs per setup, and the part requires one setup, since all features are approached from the top. $\tau_B^{mx}(\alpha)$ and $\tau_B^{dx}(\alpha)$ are the tool travel times for milling and drilling, respectively. These times depend upon the tool travel time for tool changes and the number of required tool changes. The time per change is equal to 1 minute [40]. For Plant B, $\tau_B^{mx}(\alpha) = 3$ mins per part (since three tools are required: one for the large pocket, one for the small pocket and the cutouts, and one for the corners). $\tau_B^{dx}(\alpha) = 1$ min per part (since the holes require the same tools). $\tau_B^{mm}(\alpha)$ and $\tau_B^{dm}(\alpha)$ are the cutting times for milling and drilling, respectively. These times are a function of the material removal rates, which depend upon the parameters in the generic process information model and the feature volumes given in the OOGT information model. These data are used by Lam [39] in cutting time estimation equations given by METCUT [41] and DeGarmo *et al.* [13]. For Plant B, $\tau_B^{mm}(\alpha) = 0.5$ mins per part and $\tau_B^{dm}(\alpha) = 0.2$ mins per part. N_{Bm} and N_{Bd} are the effective lot sizes for milling and drilling, respectively, and are given by Equation (2). The yield for each process, computed above, is 0.9737. Therefore, $N_{Bm} = 200/0.9737 = 206$ and $N_{Bd} = 200/0.9737 = 206$. Therefore, for a production quantity of 200 parts the machining lead time at Plant B $t_B^m(\alpha) = 4+0.5+18.21 = 22.71$ hrs or two days, since Plant B operates two eight hour shifts per day.

Table 12: Etching time elements

Time element	Time
Masking time $\tau_e^m(\alpha) = \frac{lw}{R}$	1 min/part
Photoresist stripping time $\tau_e^f(\alpha) = \frac{lw}{R}$	1 min/part
Photoresist exposure time $\tau_e^x(\alpha)$	2 min/batch
Etching time $\tau_e^e(\alpha) = \frac{D_\alpha}{0.001}$	1 min/batch

The artwork generation lead time $t_C^a(\alpha)$ at Plant C is the sum of the queue time θ_C^q, process preparation time θ_C^s, etching time $\theta_e^r(\alpha)$ and plating time $\theta_p^r(\alpha)$:

$$t_C^a(\alpha) = \theta_C^q + \theta_C^s + \theta_e^r(\alpha) + \theta_p^r(\alpha) \tag{7}$$

θ_C^q and θ_C^s are obtained from Table 8; $\theta_e^r(\alpha)$ and $\theta_p^r(\alpha)$ are derived as follows. (We assume that all of the parts are done in one batch.) The etching time is $\theta_e^r(\alpha)$:

$$\theta_e^r(\alpha) = [\tau_e^m(\alpha) + \tau_e^f(\alpha)]N_{Ce} + \tau_e^x(\alpha) + \tau_e^e(\alpha)$$

where $N_{Ce} = 200/0.9044$ is the etching lot size given by Equation (2). $\tau_e^m(\alpha)$, $\tau_e^f(\alpha)$, $\tau_e^x(\alpha)$, and $\tau_e^e(\alpha)$ are listed in Table 12. In these equations, l and w are the length and width of the product envelope from the OOGT information model; R is the masking and stripping rate (area per minute) from the generic process information model; and D_α is the etching thickness from the OOGT information model. The manufacturing engineers of Westinghouse ESG provided the photoresist exposure time of two minutes per batch. Coombs [12] provides the etching rate of 0.001 inches per minute. Therefore $\theta_e^r(\alpha)$ is 7.42 hrs. The plating time $\theta_p^r(\alpha)$ for the batch is the sum of the electroless plating and the electroplating times [12]:

$$\theta_p^r(\alpha) = \frac{(0.04)\delta_\alpha}{0.0000015} + (0.96)\delta_\alpha AF\frac{\rho_\alpha v}{w_a f}$$

In the equation above, the first term is associated with electroless plating and the second term with electroplating; $\delta_\alpha = 0.0001$ is the plating thickness, $A = 21$ in^2 is the plating area of each part, $F = 96485.31$ C/mol is Faraday's constant, $\rho_\alpha = 0.1$ lb/in^3 is the substrate material density, $v = 1$ is the copper valency, $w_a = 63.55$ is the atomic weight of copper, and $f = 0.01$ is the current density. $\theta_p^r(\alpha)$ is 0.55 hrs. Substituting these values into equation (7) yields $t_C^a(\alpha) = 11.48$ hrs or one day, assuming Plant C operates two eight hour shifts per day. Using Equation (7) for Plant D and substituting the appropriate values from Table 8 yields $t_D^a(\alpha) = 30.59$ hrs, which requires four days if Plant D operates one eight hour shift per day.

The assembly lead time $t_C^{a_m}(\alpha)$ at Plant C is the sum of the queue time θ_C^q, process preparation time θ_C^s, and the automated and manual assembly times:

$$t_C^{a_m}(\alpha) = \theta_C^q + \theta_C^s + \frac{N_A N_{Ca}}{R_A} + \frac{N_M N_{Cm}}{R_M} \tag{8}$$

For Plant C, $\theta_C^q = 4$ hrs and $\theta_C^s = 0.5$ hrs are the queue and process preparation times, respectively (Table 8). N_A is the number of automatically mounted components per part, and N_M is the number of manually mounted components per part. For this design (see Table 6) $N_A = 1$ and $N_M = 2$. N_{Ca} and N_{Cm} are the effective lot sizes for automated and manual assembly (see Equation 2). Using the yields for Plant C (Table 11), $N_{Ca} = 200/0.9876 = 203$ and $N_{Cm} = 200/0.85 = 236$. R_A is the automated assembly rate in components per hour, and R_M is the manual assembly rate in components per hour. As shown in Table 8, for Plant C $R_A = 90$ and $R_M = 60$. Substituting these values into equation (8) yields $t_C^{am}(\alpha) = 4 + 0.5 + 2.25 + 7.84 = 14.59$ hrs, or one day since Plant C operates two eight hour shifts per day. Using Equation (8) for Plant D and substituting the appropriate values from Table 8 yields $t_D^{am}(\alpha) = 12 + 2 + 1.33 + 8.42 = 23.75$ hrs, which requires three days, if Plant D operates one eight hour shift per day.

The testing lead time $t_C^t(\alpha)$ at Plant C is the sum of the queue time θ_C^q, process preparation time θ_C^s, and the testing time:

$$t_C^t(\alpha) = \theta_C^q + \theta_C^s + \theta_C^r(\alpha)N_{Ct} \tag{9}$$

where θ_C^q and θ_C^s are the queue and process preparation times. For Plant C, $\theta_C^q = 4$ hrs and $\theta_C^s = 0.5$ hrs (Table 8). $\theta_C^r(\alpha)$ is the average testing time per part. Based on information obtained by interviewing the manufacturing engineers of Westinghouse ESG, we estimate for this example $\theta_C^r(\alpha) = 0.3$ hrs per part. N_{Ct} is the lot size for testing (Equation 2). Since the testing yield is 100 percent, $N_{Ct} = 200$. Therefore, $t_C^t(\alpha) = 4 + 0.5 + 60 = 64.5$ hrs or 5 days since Plant C operates two eight hour shifts per day.

Cost

The possible cost components include the machining cost at Plant B, the artwork generation cost at Plant C or D, the assembly cost at Plant C or D, and the testing cost at Plant C. These costs are evaluated below. The manufacturing resource model provides the relevant performance data, as shown in Tables 7 and 8.

The machining cost $c_B^m(\alpha)$ at Plant B is given by equation (3):

$$c_B^m(\alpha) = (1 + \rho_B^h)[\rho_B^s\theta_B^s + \rho_B^r\theta_B^o(\alpha)] \tag{10}$$

where $\rho_B^h = 185\%$ is the overhead rate at Plant B, $\rho_B^s = \$20$/hr is the setup labor rate at Plant B, $\rho_B^r = \$20$/hr is the run labor rate at Plant B, $\theta_B^s = 0.5$ hr is the process preparation time for machining, and $\theta_B^o(\alpha) = 18.21$ hrs is the total machining time. Therefore, the machining cost at Plant B is $c_B^m(\alpha) = \$1066.57$ or $5.33 per part.

The artwork generation cost $c_C^a(\alpha)$ at Plant C is given by equation (3):

$$c_C^a(\alpha) = (1 + \rho_C^h)[\rho_C^s\theta_C^s + \rho_C^r\theta_C^o(\alpha)] \tag{11}$$

where $\rho_C^h = 1.5$ is the overhead rate, $\rho_C^s = \$25$/hr is the setup labor rate, $\theta_C^s = 0.5$ hrs is the process preparation time, $\rho_C^r = \$25$/hr is the run labor rate, and $\theta_C^o(\alpha)$ is the etching and

Table 13: Process-Plant Times and Costs

Process & Plant	Lead time (days)	Cost (per part)
machining at Plant B	2	\$5.33
artwork generation at Plant C	1	\$2.64
artwork generation at Plant D	4	\$3.45
assembly at Plant C	1	\$2.61
assembly at Plant D	3	\$3.75
testing at Plant C	5	\$18.91

plating time which is being costed. The latter is given by:

$$\theta_C^o(\alpha) = [\tau_e^m(\alpha) + \tau_e^f(\alpha)]N_{Ce} + \tau_e^x(\alpha) + \tau_p(\alpha)$$

where $\tau_e^m(\alpha)$, $\tau_e^f(\alpha)$, and $\tau_e^x(\alpha)$ are obtained from Table 12; $\tau_p(\alpha) = 0.55$ hrs is the plating time; $N_{Ce} = 222$ is the etching lot size given by equation (2), and we assume that all parts are processed in one batch. Substituting these values into equation (11) yields $c_C^a(\alpha) =$ \$528.70 or \$2.64 per part. Using Equation (11) for Plant D and substituting the appropriate values from Table 8 yields $c_D^a(\alpha) =$ \$689.21 or \$3.45 per part.

The assembly cost $c_C^{am}(\alpha)$ at Plant C is given by equation (3):

$$c_C^{am}(\alpha) = (1 + \rho_C^h)[\rho_C^s\theta_C^s + \rho_C^r\theta_C^r(\alpha)]$$

where $\rho_C^h = 1.5$ is the overhead rate, $\rho_C^s =$ \$25/hr is the setup labor rate, $\theta_C^s = 0.5$ hrs is the process preparation time, $\rho_C^r =$ \$25 is the run labor rate, and $\theta_C^r(\alpha) = 7.84$ hrs is the manual assembly time given in equation (8). Substituting these values into the above equation yields $c_C^{am}(\alpha) =$ \$521.45 or \$2.61 per part. Using the above equation for Plant D and substituting the appropriate values from Table 8 yields $c_D^{am}(\alpha) =$ \$750.32 or \$3.75 per part.

The testing cost $c_C^t(\alpha)$ at Plant C is given by equation (3):

$$c_C^t(\alpha) = (1 + \rho_C^h)[\rho_C^s\theta_C^s + \rho_C^r\theta_C^r(\alpha)]$$

where $\rho_C^h = 1.5$ is the overhead rate, $\rho_C^s =$ \$25/hr is the setup labor rate, $\theta_C^s = 0.5$ hrs is the process preparation time, $\rho_C^r =$ \$25/hr is the run labor rate, and $\theta_C^r(\alpha) = 60$ hrs is the testing time. Substituting these values into the above equation yields $c_C^t(\alpha) =$ \$3781.25 or \$18.91 per part.

Table 13 summarizes the lead time and costs for each process-plant combination in the PPDS.

6 Partner Selection

Partner selection follows the generation and evaluation of manufacturing alternatives. The partner selection approach allows the designer to identify the most suitable manufacturing processes to realize the product design and the most preferable manufacturing plants to perform these processes. The partner selection approach was constructed by Gupta and Nagi, who described it in [22]. The following provides a summary of their approach and its implementation.

6.1 Partner Selection Approach

An explicit enumeration technique constructs from the process-plant pairs in the PPDS the alternative high-level process plans. Each plan is evaluated with respect to cost, quality, lead time, and the transportation cost between consecutive plants in the process plan. The transportation cost is proportional to the distance between the states where the plants reside. The performance of each process plan depends upon the cost, quality, and lead time for the component process-plant pairs.

The designer may reduce the number of alternatives under consideration (1) by excluding those alternatives that are dominated by some other alternative with respect to any combination of criteria, and (2) by excluding those alternatives that are inferior with respect to user-specified thresholds for one or more criteria. The designer can sort the remaining alternatives on a linear combination of selected criteria. The designer provides a weight for each performance criterion, and the weighted combination of the criteria forms the new performance criterion. For example, these weights allow the designer to convert all criteria to dollars.

Alternatively, the designer can specify preferences in the form of natural language expressions concerning the importance of each performance attribute (cost, quality, lead time). Using Fuzzy-AHP, a fuzzy extension of the Analytic Hierarchy Process [64, 65], the system combines these preferences with existing data (from industrial surveys and statistical analysis) to re-emphasize attribute priorities. These redefined attribute priorities reflect the specific needs of the firm for this product. In the Fuzzy-AHP procedure, the pairwise comparisons in the judgment matrix are fuzzy numbers that are modified by the designer's emphasis. Using fuzzy arithmetic and α-cuts, the procedure calculates a sequence of weight vectors that will be used to combine the process plan's scores on each attribute. The procedure calculates a corresponding set of scores and determines one composite score that is the average of these fuzzy scores.

Table 14: Process Plan Performance

	Process Plan λ_1	Process Plan λ_2	Process Plan λ_3	Process Plan λ_4
Total yield $Y(\alpha, \lambda_i)$	0.6510	0.7368	0.5992	0.6781
Total lead time (days) $T(\alpha, \lambda_i)$	9	11	12	14
Total cost (per part) $C(\alpha, \lambda_i)$	\$29.49	\$30.63	\$30.29	\$31.44

6.2 Example

Consider now the four high-level process plans generated in Section 4 (Table 10) and the process-plant combinations evaluated in Section 5. Table 14 compares the total yield, time, and cost of each plan. The total yield $Y(\alpha, \lambda_i)$ is the product of the process yields, which are shown in Table 11. The total lead time $T(\alpha, \lambda_i)$ is the sum of the process lead times, and the total cost $C(\alpha, \lambda_i)$ is the sum of the process costs, which are shown in Table 13. The transportation costs and times between Plants B, C, and D are not considered.

Plan λ_3 does not deserve further consideration, because the total lead time and per part cost are greater than that of plan λ_1, and the total yield is worse. Similarly, Plan λ_4 does not deserve further consideration, because the total lead time and per part cost are greater than that of plan λ_2, and the total yield is worse. The designer should choose either plan λ_1 or λ_2 by balancing the shorter lead time and cost of the first against the improved yield of the second.

7 Implementation

The development of the software system that implements the method for generative design evaluation and partner selection has been inspired by a target application of the U.S. Army Tank-Automotive Command (TACOM) [42]. In this application designers and procurement agents will use the system to identify and evaluate potential sources of parts for new designs, or to determine manufacturers of spare parts for in-service products.

The system includes a menu-driven user interface that employs SUIT, an open domain subroutine library for graphics [11]. The entities of the OOGT information model and the manufacturing resource model were defined in EXPRESS, used to construct C++ classes, and were implemented in the ObjectStore object-oriented database management system [51].

We have developed the feasibility assessment, manufacturability assessment, and partner selection routines using C++ and the ObjectStore data manipulation language (DML) [51]. The system includes a design tool that allows the user to construct an ACIS solid model of a design.

The feasibility and manufacturability assessment routines provide the user with detailed reports that describe the feasibility (or infeasibility) and the performance (cost, quality, and lead time) of each manufacturing process at each manufacturing plant. The user can take this feedback into account when modifying the design to increase its manufacturability.

A complete description of this research and the software system can be found in the following reports [42, 43, 44, 45].

8 Summary and Conclusions

This paper describes a generative approach that supports a design team in critiquing a new design and in selecting the partners whose capabilities and performance best fit the design's requirements. The research focused on flat mechanical and electromechanical products; a typical application is a microwave module.

To support our approach we have developed a significant information infrastructure which consists of novel ways to represent product designs and model the capabilities and performance of manufacturing firms. We have developed high-level process planning and plan-based design evaluation procedures as well as a multi-criteria partner selection technique. The plan generation procedures use critical product design attributes (which are stored in an object-oriented group technology information model) and information about the manufacturing capabilities and performance of candidate manufacturers to generate feasible manufacturing alternatives for the new product. These alternatives may involve more than one manufacturer and are evaluated with respect to several metrics, cost, lead time, and quality. The evaluation procedures provide feedback to the designer, who can then consider modifications that improve the fit between the design and the partners. Based on the evaluation results, the partner selection procedure supports the synthesis of the most appropriate manufacturing partnerships.

In applications, such as the one in TACOM, the system architecture of Figure 1 may be implemented in a centralized manner; i.e., the system's data are maintained by the system's user. For the variant method this requires the user to maintain a database of GT codes and OOGT models of products manufactured by potential partners. To generate the information, the user (or the partners) may use the automated OOGT processor. A more practical implementation of the system is the distributed one, in which the system's services are available through a broker. The algorithms and a major portion of the information infrastructure of OSPAM reside with a provider of partnering services (on a separate server),

which is accessed through the broker. The designer's site is the client; only the CAD system resides at this site. The manufacturing resource models (including the product OOGT models) of potential partner firms are owned and maintained locally by these manufacturers.

We are currently developing mechanisms to implement the designer-broker-service interaction. In our implementation we are using Bentley Systems Microstation CAD system. The output of the system is a STEP file, which contains geometry/topology/form features and application features information. We are using a Web browser to facilitate the dialog between the designer, the broker, and the OSPAM partnering service.

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